Auditory Masking by
Single and Double Sinusoids

By

JOHN C. BOOTH, II

A DISSERTATION PRESENTED TO THE GRADUATE COUNCIL OF
THE UNIVERSITY OF FLORIDA IN PARTIAL
FULFILLMENT OF THE REQUIREMENTS FOR THE DEGREE OF
DOCTOR OF PHILOSOPHY

UNIVERSITY OF FLORIDA
1971

TO SUSIE,

DONNA AND DANNY

ACKNOWLEDGMENTS

I would like to express my sincere gratitude to my chairman, advisor and friend, Dr. John F. Brandt, whose patience and guidance throughout the course of my academic years were greatly appreciated. I also wish to thank the members of the dissertation committee for their interest and their support in this investigation.

I further acknowledge my indebtedness to the faculty, staff and students of the Communication Sciences Laboratory for their support; in particular to Wayne D. Harrington for his assistance in the design of the RCS system. A special note of thanks goes to Drs. Donald C. Teas and Donald W. Nielsen who read and critically reviewed the original manuscript.

I wish to express my appreciation and gratitude to my wife, whose understanding and cooperation were instrumental in the achievement of my educational goals. Her encouragement and dedication have been a source of strength. As my subject and typist, she provided invaluable support in this investigation.

Appreciation is also extended to the National Institutes of Health for financial support in the form of a pre-doctoral traineeship during the period. In addition, the research was supported from funds provided by the Graduate School of the University of Florida and the National Institutes of Health (Grant NB 06459).

TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

Abstract of Dissertation Presented to the
Graduate Council of the University of Florida in Partial Fulfillment
of the Requirements for the Degree of Doctor of Philosophy

AUDITORY MASKING BY
SINGLE AND DOUBLE SINUSOIDS

By

John C. Booth, II

August, 1971

Chairman: John F. Brandt
Major Department: Speech

In the investigation of auditory masking, the results have been interpreted in view of the critical band. Ideal frequency-response characteristics have been sought in the masking patterns of sinusoids and noises. With the exception of single-sinusoid masking, the results are generally consistent with the critical-band hypothesis. This investigation attempts to determine the role of the critical band in the relation between single-sinusoid masking and two-sinusoid masking. A simple power summation (3 dB) in masking was expected whenever the amounts of masking were equal.

Three masking conditions were used: masker-above, masker-below and maskers-combined. The amount of masking was determined for each of the conditions at test frequencies from 400 to 3000 Hz. The effect of psychophysical procedure was also determined (Békésy vs. BUDTIF). Monaural masked thresholds were obtained for two listeners using both threshold procedures. The masker spacings were 100, 300 and 500 Hz in the maskers-combined condition.

The results of this investigation indicate that psychophysical procedure is not significant in determining the pattern of masking, but is significant in the absolute amount of masking measured. For all spacings used, more masking was observed for the masker above the signal in frequency than when it was below. The 100 Hz spacing data showed more masking summation than expected. The pattern of summation was found to be consistent with a critical-band interpretation. The 300 Hz spacing data revealed a subject difference in the pattern of summation. This difference was attributed to frequency selectivity differences which were also reflected in the amount of masking measured. For the 500 Hz spacing, the masking summation pattern was not explainable using the critical-band hypothesis. The masking curves for the maskers-combined condition were not distinguishable from the masker-above condition.

It was hypothesized that the results of this investigation could be explained by the overlap of the displacement patterns of the signal and masker(s) along the basilar membrane. Additionally, it was hypothesized that the masking critical band is essentially a peripheral phenomenon. For wide masker separations, inhibition processes produce localized effects in the masking pattern.

CHAPTER I

INTRODUCTION

The analogy of bandpass filters as being representative of the analyzing characteristics of the ear was proposed by Fletcher (1940). In his description, Fletcher called these bandpass filters "critical bands." Fletcher advanced two assumptions about the critical band which have since generated extensive research efforts. The first assumption holds that only the energy in a narrow frequency region centered around the test signal is effective in masking it. An implication of this assumption is that the critical band is a bandpass filter which exists as part of the organizational characteristics of the auditory system. The second assumption holds that the energy of a test signal just detectable in wide-band noise is equal to the energy in the critical band. This implies a procedure whereby one might measure the critical bandwidth without using noise bandwidth as a parameter. Specifically, in order to determine the critical bandwidth for a given frequency, all one must measure is the threshold signal-to-noise ratio for that frequency in wide-band noise. This procedure has become known in the literature as the "critical ratio" method. Fletcher (1940), Hawkins and Stevens (1950), Egan and Hake (1950), Bilger and Hirsh (1956) and van den Brink (1964) have

empirically determined the signal-to-noise ratio of sinusoidal test signals in wide-band noise. Of these studies, the most extensive was that of Hawkins and Stevens (1950). Their calculated values of the critical bandwidth as a function of frequency are in agreement with those of Fletcher (1940).

Fletcher's first assumption has suggested to many investigators that manipulation of the noise bandwidth parameter is an approach in determining critical bandwidths. Because of Fletcher's limited amount of data on the masking by variable bandwidths of noise, the literature contains many studies in this area. Shafer, Gales, Shewmaker and Thompson (1950), Egan and Hake (1950), Feldtkeller and Zwicker (1956), Hamilton (1957), Greenwood (1961a), Saito and Watanabe (1961), and Bos and de Boer (1966) have used the bandwidth of narrow-band noise as a parameter. Of these investigations, that of Greenwood (1961a) is the most thorough. His estimates of critical bandwidth as a function of frequency are somewhat larger than those of Fletcher (1940), but are, in general, in agreement with others in the literature using narrow-band noise maskers. One characteristic of the narrow-band noises used in his investigation was that the attenuation slope at the cutoff frequency varied. Shafer et al. (1950) used synthetic noise constructed from sinusoid generators. Greenwood amplitude-modulated low-pass noise to obtain narrow-band noises. The slopes of the noise bands varied from 460 to 200 Hz/octave depending on the center frequency. This fact may account for some of the variation in the measured critical bandwidths between the Shafer et al. and Greenwood studies. Indeed, it has been

suggested by Scharf (1970) that the difference between the measures of Greenwood (1961a) and others lies in the fact that a 40 Hz spectral gap existed in the center of Greenwood's noise bands. It is interesting to note that Carterette, Friedman and Lovell (1969), using threshold procedures similar to that of Greenwood (1961a) for masking by a computer-generated noise, found different results. Whereas Greenwood had found a smooth masking function across the top of his narrow-band noises, Carterette _et al_. found sizeable systematic edge effects. It appears that the spectral shape of the noise is, in all probability, a factor affecting the characteristics of critical bandwidth.

Several investigators have questioned the use of narrow-band noise in determining critical bandwidths. Bos and de Boer (1966) suggest that the masked threshold for very narrow bandwidth noise is an intensity difference limen, and therefore unsuited for the determination of the critical bandwidth. Egan and Hake (1950) report that the signal-to-noise ratio, i.e., "critical ratio," differed by 4.2 dB for two supposedly supracritical bands of noise. The wider noise band produced a greater amount of masking, and therefore a larger critical ratio. One methodological procedure available to avoid these problems is to use a two-sinusoid masker. The method has been used by Zwicker (1954), Greenwood (1961a), Green (1965), Brandt and Booth (1970) and Booth and Brandt (1970) to investigate the critical band. The method uses two sinusoids to delineate the critical bandwidth, possibly with a degree of accuracy a magnitude greater than that provided by narrow-band noises. The very nature of the sinusoidal maskers permits one to

describe the bandwidth characteristics in very exacting terms. Except for the Booth and Brandt study, the procedure has been to hold the center frequency constant and vary the spacing between the components of the masker to delineate the critical band. Booth and Brandt held constant the spacing between the components of the masker and varied both the signal frequency and the maskers.

The findings using the two-sinusoidal masker procedure fall into two groups. Zwicker (1954) and Greenwood (1961a) report masking patterns which are shaped as one would predict using the analogy of a bandpass filter; i.e., the masking pattern resembles the frequency response of a bandpass filter. The results reported by Green (1965), Brandt and Booth (1970) and Booth and Brandt (1970) question the hypothesis of a simple summation of energy within a filter to explain certain portions of their data. Their results suggest that the masking of a test signal at the center of a hypothetical critical band is not a simple summation of the energy in the critical bandwidth. Green (1965) found that the masking of the test signal (a sinusoid) decreased continuously as spacing was increased. In order to obtain frequency-dependent critical bandwidths, Green had to use a criterion of 20 dB reduction in masking. Green replicated his study using a narrow band of noise as the test signal, as had Zwicker (1954). He obtained results that were midway between his sinusoidal test signal results and those of Zwicker's using the narrow-band noise. Green concluded that it is not the bandwidth characteristics of the test signal that are important, but rather it is the effect of the sound pressure level (SPL) on the individual subjects that yields the observed differences.

Since the study of Booth and Brandt (1970) represents a significant variation of the two-sinusoidal masker paradigm and serves as the basis for the present study, a thorough description of this study is in order. The masker was obtained by suppressed carrier, single-sinusoid amplitude modulation. The two resulting sidebands served as maskers. The carrier was reintroduced (variable in amplitude) and served as the test signal. The carrier frequency was varied continuously over the frequency range 100 to 4000 Hz. The modulation frequency was held constant, thereby producing sideband components that had a spacing equal to twice the modulation frequency. This spacing is independent of carrier frequency.

The equipment was arranged to yield a continuous plot of SPL required for threshold as a function of frequency. These plots, which were referred to as masking functions, showed three distinctive characteristics or regions. In Region one little or no masking of the test signal was observed; the extent of this region was found to be both dependent on the spacing between the sidebands and the SPL of the masker. Region two was considered to be an observable local maximum in the masking function. Associated with this region was a smooth transition from Region one, typically a 20 dB or greater increase in the amount of masking which depended on the masker SPL. There was an identifiable peak in the masking function in this region, followed by a decrease in the masking function curve. The frequency location of the peak was dependent on the frequency spacing between the sidebands and on the masker SPL. Region three was characterized usually by a local minimum in masking at frequencies above the peak (Region two). This region showed more variation

between subjects than did the other two regions. The shape of the masking function varied considerably with intensity and spacing of the masker.

In the discussion of their results, Booth and Brandt applied a strict interpretation of Fletcher's critical-band hypothesis. The masking in each region was discussed as reflecting the energy of the masker that lies within a fixed bandpass filter. In Region one the first assumption of Fletcher implies there is no masking of the test frequency. The two masking components and the test frequency fall into different critical bands as the spacings used were greater than critical bandwidth for frequencies below 1000 Hz (Scharf, 1970). Therefore, the critical band centered on the test frequency should contain no energy other than the test frequency. Implicit in this discussion were the assumptions that the signal determines the critical band and that the critical-band filter is rectangular in shape. The latter assumption is surely incorrect in view of the smooth transition from Region one into Region two observed by Booth and Brandt and from the findings of Schafer, <u>et al</u>. (1950).

The peak in the masking function for Region two was interpreted by Booth and Brandt to be the frequency at which critical band is equal to the frequency spacing between the sinusoidal components of the masker. The shape of the masking function predicted by Fletcher's hypothesis produces a discontinuity in the function. When both components are outside the critical band, there is no masking. When the components fall into the critical band, masking occurs which is proportional to the total energy within the filter. The existence of such a discontinuity was not evident in the masking functions reported by Booth and Brandt.

In Region three, i.e., for the frequencies above the peak, the decrease in masking found by Booth and Brandt was also inconsistent with Fletcher's critical-band hypothesis. One implication of the bandpass filter analogue for masking is that if a frequency component is located within the pass-band of the critical band, it contributes to the masking of the test signal at the center frequency by an amount proportional to the total energy of the masker. The literature on the critical band well establishes that bandwidth increases with frequency. This being the case, it is difficult to explain the increase in masking above the local minimum (Region two) observed by Booth and Brandt. The shape of the critical band which one must assume to account for the observation does not conform to the shapes hypothesized in the literature. Schafer <u>et al</u>. (1950) suggested that the pass-band is approximately single tuned, whereas Fletcher (1940) implied that the pass-band is flat. However, if one assumes that the critical band is itself a set of fixed-frequency filters which have overlapping cutoff slopes with finite rolloff characteristics, then a gross explanation of the masking functions reported by Booth and Brandt is possible. The observed local minimum in the masking curve could then be said to represent a point along the frequency continuum where two adjacent filters overlap and for which the cutoff frequencies are different. The difference in cutoff frequencies produces a minimum in the masking curves. A question then arises as to why a series of local minima is not observed.

The course of the masking function above the peak raises some question as to the plausibility of the traditional critical-band

hypothesis. Might not the masking function curves described by Booth and Brandt be explainable in terms of a single-sinusoid masking? In general, the literature concentrates on the spread of masking to frequencies above a single masker. Masker frequency is not the specific parameter of interest, but rather the asymmetry of masking. Wegel and Lane (1924), Ehmer (1959), Small (1959) and Carter and Kryter (1962) have investigated masker frequencies between 50 and 8000 Hz in various step sizes ranging from several hundred cycles to an octave. The data available from these investigations do not provide enough frequency resolution to approximate the masking curves of Booth and Brandt (1970). In order to synthesize such curves, sinusoidal masking data need to be collected for which there is maintained a constant frequency difference between the test and masking frequencies as a function of frequency.

The purpose of the present study, therefore, is to investigate the two-sinusoid masking paradigm with emphasis on the role of the individual components. The effect of each component will be determined in each region of the masking function as described by Booth and Brandt (1970). Also the effects of psychophysical procedure on the peak in Region two will be determined. Thus, the relation of single-sinusoid masking to two-sinusoid critical-band type masking is of primary concern.

It is a paradox that the critical-band hypothesis has been used to explain two-sinusoid masking in the literature and rejected in its applicability to single-sinusoid masking. Certain experimental results are unaccounted for by the critical-band hypothesis. In particular, the upward spread of masking observed by Wegel and Lane

(1924), Egan and Hake (1950), Ehmer (1959), Small (1959), Finck (1961) and Carter and Kryter (1962) is not predicted. Likewise the phenomenon of "remote masking" reported by Bilger and Hirsh (1956) is not predicted. It should be noted, however, that remote masking is not a consideration if one uses a sinusoidal masker. Spieth (1957) and Deatherage, Bilger and Eldredge (1957) found little or no remote masking for sinusoids. The phenomenon of remote masking has been shown by Deatherage <u>et al</u>. (1957) to be dependent on envelope variation. In the case of the sinusoid, the envelope is constant, and therefore no remote masking is found. In the case of sinusoidal amplitude modulation, there is envelope variation and there is remote masking. In this instance, an additional parameter of the masker, i.e., its envelope, determines portions of the masking function.

In the present study, the masking function produced by a two-sinusoid masker at several center frequencies was obtained. At each of these center frequencies, the masking was also determined for the lower frequency component alone and for the upper frequency component alone. The summation of these two amounts of masking was calculated and compared to the summation found when both components were used as masker. The summation of masking is a phenomenon that has been reported for two noises, a noise and a sinusoid, but not for two sinusoids.

It has been noted that for two bands of noise there is an increase in masking at the crossover frequency of the masking patterns when the two are added. Webster, Miller, Thompson and Davenport (1952) report a 7 dB increase, suggesting to them an

"in-phase addition process." Bilger (1959) reports a 6 dB increase for his two highest SPLs and the expected 3 dB power summation at the lowest SPL. He explains his results by assuming he is summing two types of masking, i.e., upward spread of masking caused by distortion products and critical-band type masking. In the present study, a single masker level of 40 dB was used to minimize the spread of masking to high frequencies and leaving, according to Bilger, critical-band type masking.

In the present experiment, the relation of single-sinusoid masking to two-sinusoid masking in each region of three critical bands, 100, 300 and 500 Hz, was investigated. This range provides a reasonable variation in the critical bandwidth center frequencies, as reported by Scharf (1970). In order to provide a body of data from which the answers to this question and others can be hypothesized, a psychophysical procedure (BUDTIF, Campbell and Lasky, 1968) yielding finer threshold resolution than that used by Booth and Brandt (1970) (Békésy tracking) was used. An adaptive technique appeared to be well suited to this psychophysical task. Unlike the fixed methods, it required no prior knowledge of the psychometric function and was more efficient with respect to the time required to obtain threshold values.

CHAPTER II

PROCEDURE

Subjects

Two listeners with four hours of training in the BUDTIF procedure were used as subjects. The subjects were selected for their ability to do the task and their availability. Between-day threshold variability [equal to or smaller than that reported by Campbell and Lasky (1968)] and a rapid response were the two criteria for judging their ability to perform the task.

Masking Stimuli

The masker was generated using a general-purpose linear integrated circuit, Motorola MC1545. The circuit was operated as a suppressed carrier amplitude modulator adapted from Application Note 475 in The Microelectronics Data Book (1969). The wide-band frequency characteristic of this circuit permits the use of high carrier and modulator frequencies relative to the ear's range of greatest sensitivity. The carrier frequency and the modulation frequencies were chosen so that only the lower of the two sidebands fell into the frequency interval of 400 Hz to 3000 Hz. The other sideband lies well above the ear's range of greatest sensitivity,

and both the upper sideband and the carrier frequency are well above the frequency response of the earphone. Since suppressed carrier amplitude modulation yields spectral components that are equal to the carrier frequency plus and minus the modulation frequency, one and two modulation frequencies were used to generate the one and two component maskers, respectively. The spacing between the components in the masker is determined by the absolute frequency difference between the modulation frequencies. As the frequency of the carrier is increased, the frequency of the sidebands increases, but the spacing between the components remains constant. The generation of the masker in this manner was required to obtain the Békésy tracking data. The frequency spacings between the two component maskers were 100, 300 and 500 Hz; in the case of the single component maskers, half of this spacing was used above and below the test frequency. The two component masker SPL was 40 dB, while each of the single component masker SPLs was 37 dB.

Test Signal

The test signal was obtained by mixing an additional modulation frequency with the masker modulation frequencies. The frequency of this modulator was adjusted such that its component in the sideband was in the desired frequency relation to the masking component(s). Its amplitude was variable and adjusted in accordance with the rules of the threshold procedure being used. In the Békésy procedure, threshold was obtained over the range 0.4 to 3.0 kHz. The test frequencies used in the BUDTIF procedure were 0.4, 0.5, 0.7, 0.9, 1.0, 1.1, 1.2, 1.3, 1.4, 1.5, 1.6, 1.7, 1.8, 1.9, 2.0, 2.2, 2.4, 2.6, 2.8 and 3.0 kHz and were the same for both subjects.

Experiment I

In this experiment, continuous frequency masking curves of the kind described by Booth and Brandt (1970) were obtained. The Békésy procedure was used to obtain the threshold measurements. Fig. 1 shows the schematic diagram of the equipment used in the experiment.

The two masking component oscillators (General Radio, Model 1313-A) were mixed in a two-channel active mixer, the output of which was led to the modulator input of the Motorola MC1545. The test signal oscillator (Hewlett-Packard, Model 202) was led to an impedance matching transformer (United Transformer Company, Type LS-33) and a recording attenuator (Grason-Stadler, Model 3262A). The output of the recording attenuator was led to an impedance matching transformer (United Transformer Company, Type LS-33), then gated with a period of 200 msec and 50 per cent duty cycle by an electronic switch (Grason-Stadler, Model 829E). The gated output was led to the buffer amplifier and the modulator input of the Motorola MC1545. The output of the balanced modulator was led to a filter (Krohn-Hite, Model 3100) and an earphone (Telephonics, Model TDH-39) mounted in an MX-41/AR cushion. The filter is used to smooth the acoustic response of the stimulus generating system. The recording attenuator was controlled by the subject using a hand switch. The output of the recording attenuator also was led to the graphic level recorder (General Radio, Model 1521B). The graphic level recorder drives the carrier frequency oscillator (General Radio, Model 1304B). The recording attenuator, test signal oscillator and graphic level recorder were used as a Békésy audiometer (Békésy, 1960).

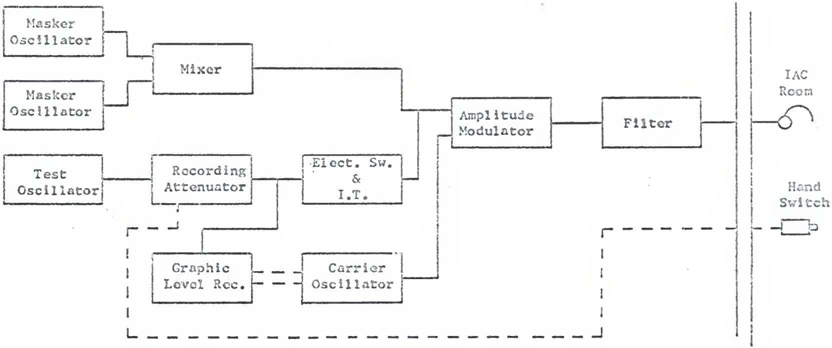

Fig. 1. Schematic diagram of equipment used in Experiment I.

Experiment II

In this experiment, fixed-frequency masking data were obtained. The BUDTIF procedure was used to obtain the threshold measurements. Fig. 2 shows the schematic diagram of the equipment used in the experiment.

The masking signal was generated in the same manner as in Experiment I. The test signal was generated in the same manner as in Experiment I, but was delivered in a different manner, as necessitated by the BUDTIF procedure. The output of the test signal oscillator (Hewlett-Packard, Model 202) was led to the random channel selector (RCS), described in Appendix B. The RCS is a special-purpose circuit that randomizes an input between two electronic switches (Grason-Stadler, Model 829E). The outputs of the electronic switches (Grason-Stadler, Model 829E) were mixed with an impedance matching transformer (United Transformer Company, Type LS-33) and attenuated (Hewlett-Packard, Model 350D). The remainder of the stimulus generating equipment was the same as described in Experiment I.

BUDTIF Procedures

The BUDTIF procedure as described by Campbell and Lasky (1968) was used in the study. The BUDTIF procedure presents levels of the stimulus in blocks of two or more trials to the subject. The performance of the subject within a block of trials determines the value of the stimulus to be used in the next block of trials. The presentation of trials within a block requires the use of a forced-choice procedure. Campbell (1969a), in a study of forced-choice procedures, reports the smallest "subject" effect for the 2IFC

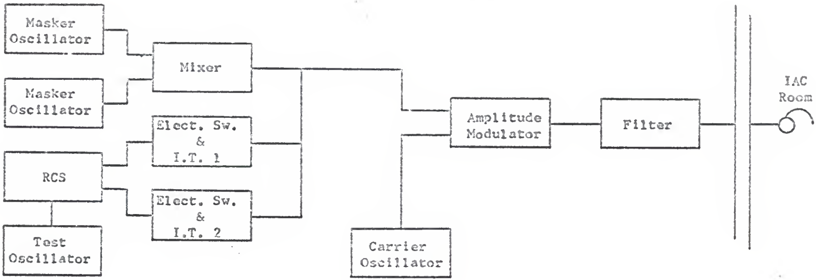

Fig. 2. Schematic diagram of equipment used in Experiments II and III.

continuous masker condition. In this condition, the signal is always presented in one of two well-defined signal intervals, while the masking stimulus is continuously presented. Since it is desired to minimize differences between subjects, the 2IFC continuous masker was used in the study. The basic goal of BUDTIF is to determine the sound pressure level for a given point on the psychometric function. For the 75 per cent correct detection point, Campbell, Hutton and Stuckey (1966) found minimal variability and bias for repeated thresholds when the block size was four trials. The target performance value of 75 per cent correct detections was used in the present experiment because its efficiency is well established (Campbell *et al.*, 1966; Campbell *et al.*, 1968; and Campbell, 1969a,b). The following decision rules were used. Each threshold run began at level 5 dB above the anticipated value from the results of Experiment I. The stimulus step size was 2 dB. The level change rules were as follows. In a block of four trials, if two or more incorrect, increase one step; if one incorrect, no change; and if zero incorrect, decrease one step. The effect of the no-change rule was to permit the subject to continue tracking at the 75 per cent correct detection point since this is the nominal target value on the psychometric function. After the fifth revisit to a stimulus level, the presentation of stimuli was terminated. The median of the revisited stimulus levels was taken at the stimulus level at which the subject was correct in his detections 75 per cent of the time. This stimulus value serves as the basic datum of this study.

Experiment III

In this experiment, fixed-frequency masking data for single sinusoid maskers were obtained. The same 20 test frequencies used in Experiment II were employed. The masker was located at a frequency spacing equal to one-half the spacing used in Experiments I and II, both above and below the test frequency. Masking observed under each of these conditions was essential in determining the summation of masking when the test frequency was masked simultaneously by both. The equipment utilized in this experiment was the same as used in Experiment II with the exception that there was a single masker modulation oscillator, the other oscillator being replaced by a 600 ohm resistor to balance the mixer. The masking data were collected using the BUDTIF procedure previously described.

Calibration Procedures

Reference voltage levels were maintained with a vacuum tube voltmeter (Ballantine, Model 321). Frequency and timing measures were made with a digital counter/timer (Monsanto, Model 101B). Acoustic stimuli were analyzed using an artificial ear (Brüel and Kjaer, Type 4152) a condenser microphone and cathode follower (Brüel and Kjaer, Type 4132/2163) and a microphone amplifier (Brüel and Kjaer, Type 2112) whose output was fed to a wave analyzer (General Radio, Model 1900A). Harmonic distortion products were typically 50 dB or more below the level of the sideband components. The wave analyzer was also used to adjust the oscillators to obtain the desired frequency spacing during each session. The overall frequency response of the stimulus generating equipment was ± 1.5 dB SPL over the frequency range of 400 to 3000 Hz.

Experimental Sessions

The masked threshold measurements were made in a sound treated room (IAC) for all three experiments. In Experiment I the subject was instructed in the Békésy procedure, the operation of the hand switch and recording attenuator. The threshold determination for each spacing lasted approximately six minutes. Each of the three experimental sessions required approximately 45 minutes with two five-minute breaks interspersed. The spacings were randomly presented within each session, with all spacings being used within a session. In Experiments II and III the subjects were cautioned that the probability of signal occurring in either of the intervals was independent of previous occurrences. The subjects were told to attend to both signal intervals before formulating a decision as to which interval contained the signal. No feedback was provided the subject. The duration of threshold runs was determined by the efficiency of the subject. Each threshold run lasted approximately ten minutes. Each experimental session lasted one hour, with one ten-minute break given midway in the session. No more than three experimental sessions per day were conducted. During each experimental session, a single masker spacing was employed; however, the test frequency was randomized. The various spacings were randomly assigned to experimental sessions with the restriction that the data for all spacings were collected prior to the repetition of a given spacing. Methodologically, then, the data for Experiments II and III were collected concurrently, but in different experimental sessions. The number of experimental sessions required to collect all the data for each spacing varied because the number of thresholds obtained

per session varied. Data collection required a six-week period to complete. Quiet thresholds for each of the 20 test frequencies used in Experiments II and III were also determined to permit the calculation of the amount of masking.

CHAPTER III

RESULTS

Effect of Psychophysical Procedure

Data were collected in the form of continuous- and fixed-frequency masked thresholds from 400 to 3000 Hz. In Experiment I continuous-frequency masked thresholds for two sinusoidal maskers were collected using the Békésy procedure. A continuous masking pattern was obtained by drawing a line through the midpoints of the Bekesy tracings. Tracings for three replications of each experimental condition were combined to form an average. In Experiment II fixed-frequency masked thresholds for two sinusoidal maskers were determined for 20 test frequencies by the BUDTIF procedure. The results of these experiments are plotted in Figs. 3 (Subject 1) and 4 (Subject 2).

The panels in each of these figures show the effects of the three spacings - 100, 300 and 500 Hz from left to right. There are two similarities in the data from the two subjects. First, the largest difference in SPL required for threshold for the two measurement procedures occurs at the 100 Hz spacing and the least occurs at the 500 Hz spacing for both subjects. Second, there are common features in the masking pattern obtained for both measurement

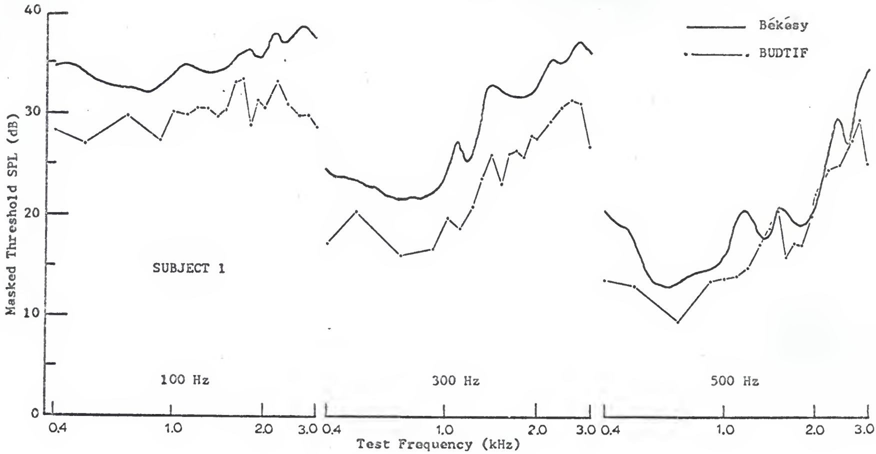

Fig. 3. Comparison of the Békésy (solid) and BUDTIF (dashed) procedures for Subject 1. Spacing for the combined-maskers from left to right are 100, 300 and 500 Hz.

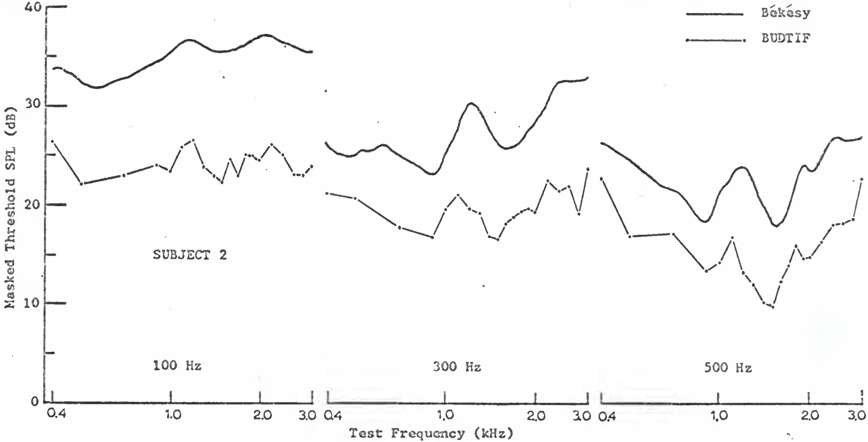

Fig. 4. Comparison of the Békésy (solid) and BUDTIF (dashed) procedures for Subject 2. Spacing for the combined-maskers from left to right are 100, 300 and 500 Hz.

procedures that are related in a systematic way. The features in the fixed-frequency curve seem to be shifted toward the lower frequencies relative to the same features in the continuous-frequency curve. Although this is not seen in every case, the trend seems to be in that direction. In general, the two measurement procedures reflect the same underlying function though the magnitude and detail may differ. The variability in repeated threshold measures for both procedures does not account for the differences observed. The greatest difference observed between threshold repetitions for the BUDTIF method was 3 dB. Typically the difference was less than 2 dB, the step size used in the procedure. The Békésy procedure yielded repetitions that were on the order of 4 to 6 dB different.

Subject 2 also served in the Booth and Brandt study (1970). His Békésy data in the present study are in good agreement with the earlier experiment.

Effect of the Individual Sinusoids in Two-Sinusoid Masking

Figs. 5 and 6 display the masked threshold curves obtained using the BUDTIF technique for Subjects 1 and 2, respectively. The panels in each figure show the effect of spacing between the two-masker sinusoids (from left to right 100, 300 and 500 Hz). In each panel three masking curves plus quiet threshold are shown. The curve labeled A is the masking pattern observed when the sinusoid masker is above the test frequency. The curve labeled B is the masking pattern observed when the sinusoid masker is below the test frequency. The curve labeled C is the masking pattern observed when both of the masking sinusoids are combined (i.e., two-sinusoid masking). In all cases the test frequencies are equal.

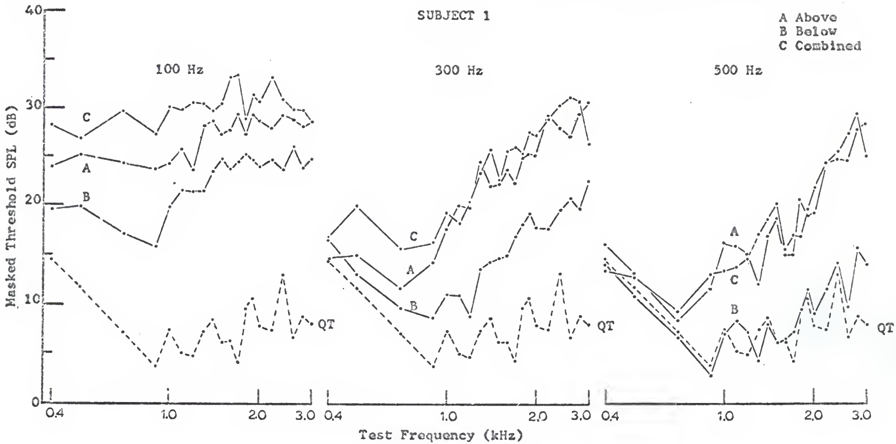

Fig. 5. Masked threshold SPL for masker(s) above (A), below (B) and combined (C) for Subject 1. Spacing for the combined-maskers from left to right are 100, 300 and 500 Hz. Quiet threshold (QT) is shown in the dotted curve.

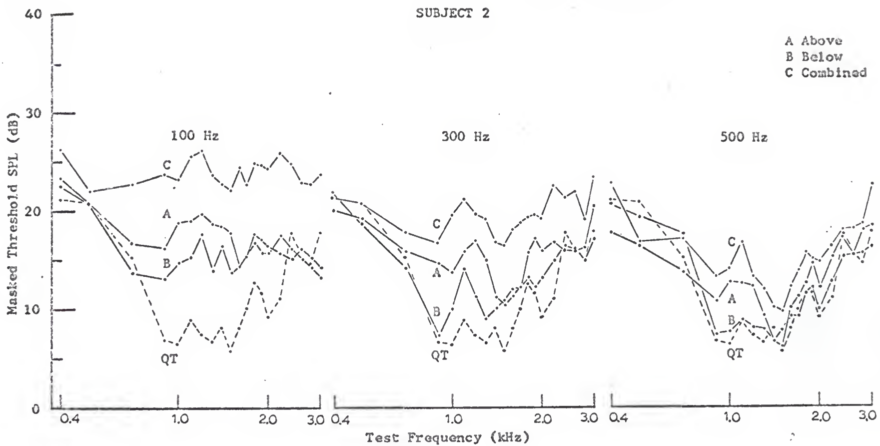

Fig. 6. Masked threshold SPL for masker(s) above (A), below (B) and combined (C) for Subject 2. Spacing for the combined-maskers from left to right are 100, 300 and 500 Hz. Quiet threshold (QT) is shown in the dotted curve.

In Fig. 5, Subject 1 shows a systematic masking pattern as a function of spacing between the sinusoids. At a spacing of 100 Hz there is clear summation of masking; i.e., either component sinusoid produces less masking than is the case when both are presented simultaneously. There is more masking observed for the higher frequency component (curve A) than for the lower component (curve B), and both are clearly different from quiet threshold.

The center panel displaying the 300 Hz results shows less summation than the 100 Hz spacing. Again, the higher component yields more masking than the lower component, but there is a greater difference between the A and B curves than when the spacing is 100 Hz. Compared to the 100 Hz condition, at low frequencies the difference is smaller; while at high frequencies the difference is larger. This feature is an important consideration in the mechanism to be proposed. For frequencies above 1000 Hz, less summation might be predicted. Indeed, it is difficult to distinguish between the masking curve for the higher component (curve A) and the masking curve for both components (curve C). It is clear that for this separation between masker and test signal the masking function for the lower component (curve B) is different from quiet threshold. It appears that at higher test frequencies the combined-maskers are really single-sinusoid (the higher one) masker functions.

The right panel of Fig. 5 shows the results when the spacing is 500 Hz between the two masking sinusoids. The masking curve for the two-sinusoid masker (curve C) is not distinguishable from that of the higher component (curve A). Similarly, the masking function for the lower component (curve B) cannot be distinguished

from the quiet threshold. At low frequencies all four curves are the same, and somewhere above 700 Hz they separate. There is no evidence of summation even in the low frequencies.

The left panel in Fig. 6 shows the results of the 100 Hz spacing for Subject 2. This subject shows more summation of masking than Subject 1. In the high frequencies (above 2500 Hz) there is little or no masking associated with either component, but their combination (curve C) shows an appreciable amount of masking.

The center panel shows the results of the 300 Hz spacing. Considerable summation of masking can still be observed, but more than that expected from a simple summation hypothesis (3 dB). Low frequencies show little or no masking for all three conditions. For the two single-sinusoid conditions, there is a region around 1700 Hz where there is no masking. Again, above 2400 Hz, as was the case for the 100 Hz spacing, there is little or no masking, but appreciable summation. The masking for the lower component (curve B) is not different from quiet threshold except over the range 1000 to 1700 Hz.

The right panel shows the results of the 500 Hz spacing. The masking due to both components (curve C) is no different than from the masking due to the higher component (curve A). This is further supported by observing that the masking measured when the lower component (curve B) is present is no different from quiet threshold. In the low frequencies, all four thresholds can be considered the same.

Above about 1700 Hz there is probably no difference in the threshold for all four conditions. The amount of masking in the region above 1700 Hz is considerably different for the subjects.

The important similarities for the subjects are as follow. When the amount of masking observed for the higher and lower components approximate each other, masking summation occurs. Also, there is a greater amount of masking associated with the higher frequency component (curve A) than with the lower component (curve B). Even though there is considerably less masking for the lower component (curve B), significant masking summation occurs. The ordering of the curves for both subjects for all spacings is that more masking occurs with the higher component than for the lower component.

The primary difference between the subjects lies in the frequency selectivity characteristics exhibited by Subject 2, but not Subject 1. While the increase in masking begins at about 900 Hz for both subjects, Subject 2 shows a minimum around 1700 Hz, which is not the case for Subject 1.

The data from Figs. 5 and 6 have been rearranged in Figs. 7 and 8. The panels from left to right are the masker(s) above, below and combined. In each panel frequency spacing is the parameter. Within a panel the curve ordering is as expected; that is, as masker location is increasingly distant from the test signal, masking decreases. Threshold SPL convergence at high frequencies occurs in all panels except the masker-below condition for Subject 1. The amounts of masking are different for the subjects. In Fig. 8 (Subject 2) a local maximum occurs in the curves in each panel between 1100 and 1200 Hz except for the 250 Hz masker-below.

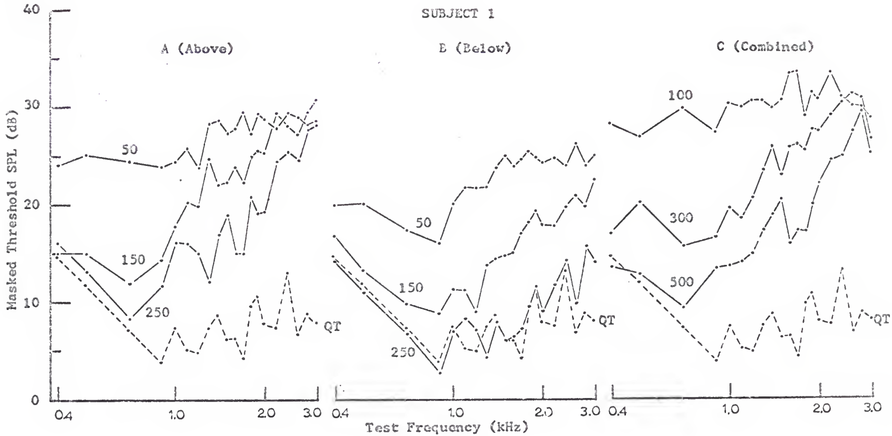

Fig. 7. Masking of test frequency as a function of distance (in Hz) from the masker for Subject 1. Masker position in panels left to right: above, below and combined. Quiet threshold (QT) is shown in the dotted curve.

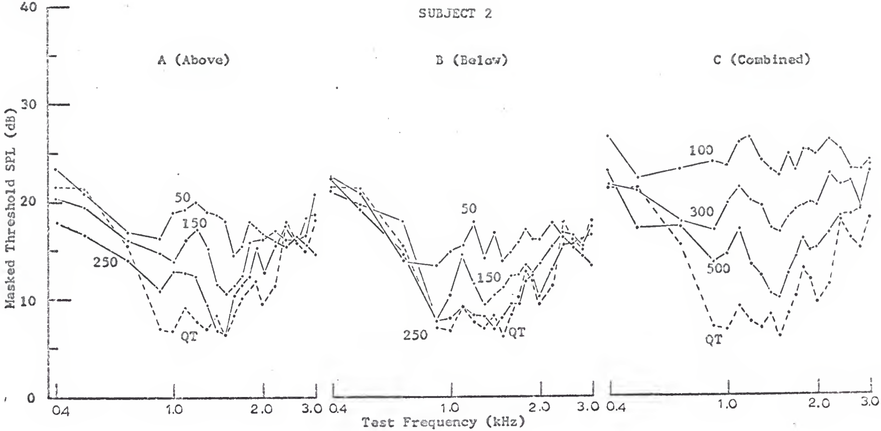

Fig. 8. Masking of test frequency as a function of distance (in Hz) from the masker for Subject 2. Masker position in panels left to right: above, below and combined. Quiet threshold (QT) is shown in the dotted curve.

CHAPTER IV

DISCUSSION

Effects of Psychophysical Procedure

One purpose of this study was to determine the effect of psychophysical method on the masking pattern produced by a two-sinusoid masker. The same stimulus generating equipment was used in both procedures and thus was not a significant source of error. As seen in Figs. 3 and 4, the two procedures produced differences in threshold SPL, with the Békésy procedures showing higher thresholds. Systematic effects in the frequency location features of the masking pattern were observed. Using the Békésy procedure, certain maxima and minima in the threshold curves were higher in frequency than the same features using the BUDTIF technique. This result is reasonable since frequency is changed continuously in the Békésy procedure. A lag in response would be expected with the Békésy procedure relative to fixed-frequency conditions of the BUDTIF procedure. The differences might also be in part the result of slack in the mechanical linkages in the Békésy system. Although the threshold criteria are different for the two procedures (i.e., frequency tracking vs. fixed frequency), it is difficult to account

for the large differences in SPL required for threshold on the basis of criteria. It is not apparent how one would account for the threshold differences, and in particular why there is a frequency spacing effect. It seems fair to conclude that the psychophysical method has a quantitative effect on the measures one makes, but that the phenomenon described by Booth and Brandt (1970) is not dependent on continuously changing frequency for its demonstration.

Summation of Masking

The primary purpose of this study was to investigate the summation of masking. The critical-band hypothesis states that when two masking sinusoids fall within the same critical band, there will be a 3 dB increment in masking whenever the individual sinusoids produce the same amount of masking of the test signal. In almost every case there was more summation of masking than predicted in the present study. For example, in the left panel of Fig. 5 at 1000 Hz there is a 4 dB difference in the masking for the two single-sinusoid conditions. The summation based on the amount of masking is predicted to be 1.4 dB. However, a 6 dB summation of masking is observed.

The amount of summation was dependent on frequency spacing, the frequency location of the stimuli, as well as individual subject differences. For the narrowest spacing, 100 Hz, summation occurred over the entire frequency range for Subject 2 (Fig. 6). Such a result is expected from the literature. Scharf (1970) reports that the smallest critical bandwidth is 100 Hz. Assuming that summation is a manifestation of the critical band, it is hypothesized that

both components fall into the pass-band and are summed. Since the critical bands are generally considered to be larger than 100 Hz, summation must occur over the whole frequency range. The results for the 300 Hz spacing show the expected summation pattern. There is little summation in the low frequencies (below about 600 Hz) and summation at higher frequencies. For a spacing of 500 Hz, there is masking summation only in a narrow frequency range around 1100 Hz. Except for the 500 Hz spacing, the masking summation observed has paralleled changes in critical bandwidth as a function of frequency. It is not clear why there is no summation above about 1500 Hz.

On the other hand, Subject 1 shows a pattern of masking summation that is different from Subject 2. For a spacing of 100 Hz there is a broad pattern of summation. However, for the 300 and 500 Hz spacings, there is no summation above 1000 Hz and only below 1000 Hz for the 300 Hz spacing. The lack of frequency dependence for wide spacings is difficult to interpret. The narrow spacings produce summation in accordance with a critical-band prediction. However, for the largest spacing, neither subject showed a summation pattern commensurate with changes in critical bandwidth as a function of frequency.

Other investigators have studied the summation of masking (Bilger, 1959; Green, 1967). The greater than 3 dB summation observed in their studies was attributed to distortion products. Bilger states that the upward spread of masking partly accounts for summation, whereas Green suggests it is detection of distortion products. In the present study, distortion products were minimized by using a masker level of 40 dB sound pressure level. Plomp (1965) reports

detectability threshold for combination tones to be generally greater than 40 dB SPL. Goldstein (1967) suggests a level of 50 dB sensation level before they are audible. These findings suggest that the generation of summation and difference tones is not significant in the determination of masked thresholds in the present study, and therefore would not account for the greater than 3 dB summation also observed in this study. (No attempt was made in the present study to psychoacoustically assess the presence or absence of combination tones. In addition, the acoustic stimulus contained no components higher than -50 dB relative to the maskers.)

Sinusoidal Masking

The unusual finding that a high frequency masks a test signal more efficiently than a lower frequency has been reported, but not directly commented upon, by Zwicker (1954) and Small (1959). Zwicker used a fixed-frequency test signal and found more masking for the masker-above condition than for the masker-below condition. Small, using a constant intensity test signal, found that for a masker-frequency/signal-frequency ratio of 0.95 and 1.05, the higher frequency masker was more efficient; i.e., it masked out the test signal at a lower SPL. For ratios 0.8 and 1.2 at low test signal frequencies, the higher frequency masker was the more efficient; as test signal frequency was increased, the lower frequency masker became more efficient.

The results of this study, as well as those of Zwicker (1954) and Small (1959), suggest that for small frequency differences between the signal and masker, the condition where the masker is

above the test signal in frequency is more efficient than the reverse condition. These results do not necessarily contradict the generalization that low frequencies mask highs more efficiently than high frequencies mask lows because the experiments on which this generalization is based use larger frequency spacing than were used here.

Amount of Masking

Conventionally, the amount of masking is defined as the threshold shift of a sound caused by the presence of another. Displayed in Fig. 9 are the amounts of masking at 1700 Hz, which are representative of the overall patterns observed. Subject 1 is 6 dB more sensitive than Subject 2. However, there are large differences in the threshold shifts for the subjects. For example, Subject 1 shows 16.5 dB more masking than does Subject 2 for the 100 Hz spacing. Subject 2 shows approximately 6 dB summation for the 100 and 300 Hz spacings. For the 500 Hz spacing, there is no summation. Subject 1 shows approximately 3 dB summation for the 100 and 300 Hz spacings. For the 500 Hz spacing, the amount of masking is the same as the masker-above condition. The shape of threshold shift curves as a function of frequency spacing is in agreement with those reported by Brandt and Booth (1970).

Possible Mechanism for Masking

Summation of masking within a critical band consistently explained only the data at the smallest spacing (100 Hz) and below 700 - 900 Hz for the 300 Hz spacing. Still unexplained were the effects of frequency spacing and masker location above the

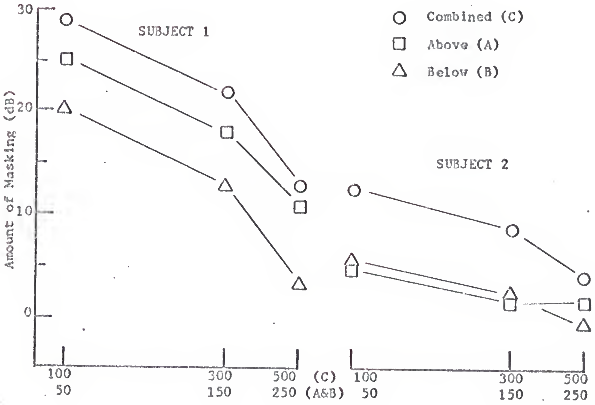

Fig. 9. Amount of masking at 1700 Hz as a function of masker spacing. The parameter is masker position: above (A), below (B) and combined (C). Left panel, Subject 1; right panel, Subject 2.

700 - 900 Hz region. An explanation in terms of the critical band is basically unacceptable for two reasons. First, the absence of summation of masking and, second, the threshold signal-to-noise ratios (S/N) did not conform to critical-band behavior.

The top of the ordinate in Figs. 5 through 8 is 0 dB S/N. According to Fletcher (1940), the S/N ratio should be 0 dB at a critical bandwidth or greater (i.e., any higher frequency). As is typical, the S/N ratios are negative in the present study. Although the absolute value of the S/N ratio is of little importance, its variation as a function of frequency is important. According to Scharf (1970), the S/N ratios expected from critical bands are as follow. A masker with a 100 Hz spacing should produce a constant threshold S/N ratio at all test frequencies, a 300 Hz spacing should produce a constant S/N ratio above 1900 Hz, and above 2600 Hz for a 500 Hz spacing. Only the 100 Hz spacing produced the predicted result. For other spacings, the threshold S/N ratio generally decreases (goes more positive toward 0 dB) with an increase in test frequency above about 700 - 900 Hz.

The 700 - 900 Hz region is where Subject 1 ceased to show summation at 300 Hz spacing and where the effects of the masker below the test signal began to disappear. It is the same region where Subject 2 began to show summation at all spacings in a narrow frequency region.

Consideration of the frequency effects brought to mind other psychoacoustic data, such as the decrease in the relative differential threshold for frequency up to about 1000 Hz (Shower and Biddulph, 1931), the constant critical bandwidth as a function of frequency

up to 1000 Hz (Scharf, 1970), the rapid decrease in absolute sensitivity up to 1000 Hz in our data, etc. Not the least was a consideration of the generalization that frequency is distributed along the basilar membrane linearly up to about 700 - 1000 Hz and logarithmically above about 1000 Hz (e.g., Greenwood, 1961b). The frequency-place representation is, of course, a mechanical (anatomical) one and suggested a possible explanation of the data in terms of a peripheral mechanism.

In Fig. 10, stylized displacement patterns along the basilar membrane are shown for each of the masker conditions. The test frequency is at 2000 Hz and the frequency-place relations (high-to-low, left-to-right) are represented logarithmically. The spacings of the maskers from the test frequency are shown from top (50 Hz) to bottom (250 Hz). The left-hand column represents masker-above (A), the center column represents masker-below (B), and the right-hand column represents the maskers-combined (C) condition. The peak of the masker-above pattern is always constant. The peak of the masker-below pattern varies by the difference in masking between the two conditions in the data from Subject 1 in Fig. 5. The difference in effective masker level is dictated first by psycho-acoustic data, which say that the amount of masking of a sinusoid by a sinusoid of each frequency is directly proportional to the masker level. Since the maskers are of equal SPL and the masker-below shows less masking, the peak of the masker-below pattern has been reduced by the difference in the amount of masking. Physiological evidence for making such an adjustment independent of masking experiments is provided by Rhode, who demonstrated with the Mossbauer

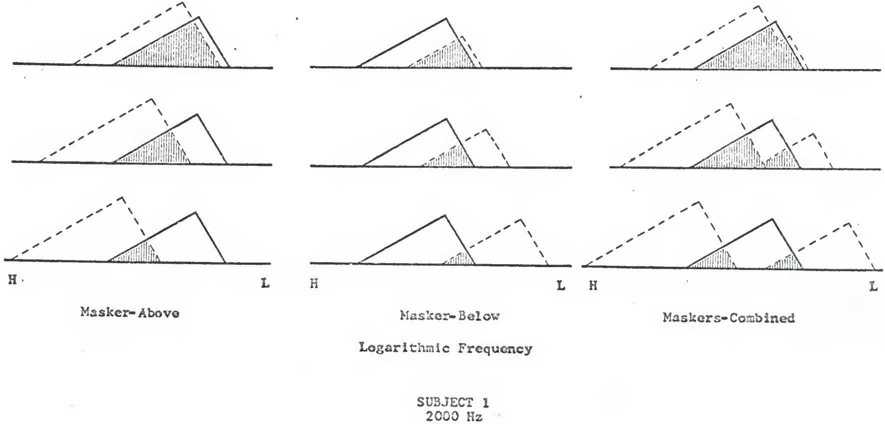

Fig. 10. Stylized displacement patterns at 2000 Hz for Subject 1. Solid curve represents test signal and dashed curve represents masker. Masker spacing from top to bottom: 50, 150 and 250 Hz. Frequency-place relations are high-to-low, left-to-right.

technique that given equal input SPL, the displacement of the basilar membrane will increase as the position of measurement moves toward the base (see Rhode, 1971, Fig. 8).

In Fig. 10, the degree of overlap (shaded area) represents the amount of masking. Note the shaded areas in the left column are larger than the shaded areas in the center column. In other words, greater masking occurs for the masker-above condition than the masker-below condition. This is precisely what the data of Subject 1 show at 2000 Hz. Examining the effects of spacing, one sees in the figure a decrease in the shaded areas with increase in spacing. Again, the psychoacoustic data show that masking decreases with increased spacing. Note, however, the masker-below condition shows no overlap at a spacing at 250 Hz, which means no masking in this condition. Indeed, the psychoacoustic data of Fig. 5 show the masker-below condition results in the same thresholds as the quiet threshold.

The maskers-combined condition is shown in Fig. 10 in the right-hand column. Again, the effects of spacing in the figure parallel the psychoacoustic data. Note, however, the 250 Hz spacing where the overlap is provided by the masker-above condition. Indeed, in Fig. 5 the A and C curves are interleaved. These conclusions appear to hold for frequencies above 1000 Hz.

The confirmation of a peripheral mechanism, i.e., interaction of displacement patterns, explaining the psychoacoustic data is shown in Fig. 11 where the stylized patterns are graphed on a linear frequency-place scale appropriate for the data at 900 Hz in Fig. 5. The conclusions are the same as discussed above and hold for frequencies less than about 900 Hz.

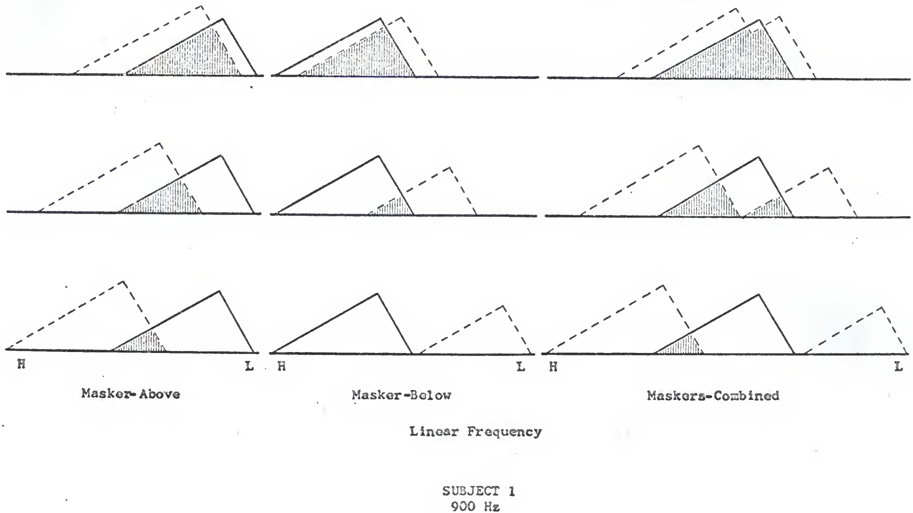

Fig. 11. Stylized displacement patterns at 900 Hz for Subject 1. Solid curve represents test signal and dashed curve represents masker. Masker spacing from top to bottom: 50, 150 and 250 Hz. Frequency-place relations are high-to-low, left-to-right.

The preceding discussion seems to explain the data of Subject 1 quite easily. It also explains the data of Subject 2. The difference between the subjects is basically that Subject 2 shows more summation over a wider frequency range for the 300 Hz spacing and in a narrow frequency range (900 - 1500 Hz) for the 500 Hz spacing. It is tempting to suggest that Subject 2 has greater frequency selectivity than Subject 1, and the frequency-localized summation regions may further represent such a differentiation. Note the difference in the size of the peaks in the masking functions obtained from the two subjects by the Békésy technique, as shown in Figs. 3 and 4.

The fact that a peripheral mechanism can explain these data makes it tempting to further speculate upon the localized summation areas seen in the sweep frequency Békésy data from this study and the localized peaks in the masking functions reported earlier by Booth and Brandt (1970) and Brandt and Booth (1970). Our earlier explanation suggested that the peaks were the result of a fixed neuro-anatomical organization of the auditory system in conjunction with inhibitory mechanisms. It appears from the present data that this is indeed the case. A peripheral mechanism easily explains the general data of Subjects 1 and 2. The peak in the masking functions from Subject 2 shows summation of masking. If summation and the critical-band behavior are related, it is tempting to suggest that the critical band is indeed a peripheral phenomenon.

CHAPTER V

SUMMARY

In the investigation of auditory masking, the results have been interpreted in view of the critical band. Ideal frequency-response characteristics have been sought in the masking patterns of sinusoids and noises. With the exception of single-sinusoid masking, the results are generally consistent with the critical-band hypothesis. This investigation attempts to determine the role of the critical band in the relation between single-sinusoid masking and two-sinusoid masking. A simple power summation (3 dB) in masking was expected whenever the amounts of masking were equal.

Three masking conditions were used: masker-above, masker-below and maskers-combined. The amount of masking was determined for each of the conditions at test frequencies from 400 to 3000 Hz. The effect of psychophysical procedure was also determined (Békésy vs. BUDTIF). Monaural masked thresholds were obtained for two listeners using both threshold procedures. The masker spacings were 100, 300 and 500 Hz in the maskers-combined condition.

The results of this investigation indicate that psychophysical procedure is not significant in determining the pattern of masking, but is significant in the absolute amount of masking measured. For

all spacings used, more masking was observed for the masker above the signal in frequency than when it was below. The 100 Hz spacing data showed more masking summation than expected. The pattern of summation was found to be consistent with a critical-band interpretation. The 300 Hz spacing data revealed a subject difference in the pattern of summation. This difference was attributed to frequency selectivity differences which were also reflected in the amount of masking measured. For the 500 Hz spacing, the masking summation pattern was not explainable using the critical-band hypothesis. The masking curves for the maskers-combined condition were not distinguishable from the masker-above condition.

It was hypothesized that the results of this investigation could be explained by the overlap of the displacement patterns of the signal and masker(s) along the basilar membrane. Additionally, it was hypothesized that the masking critical band is essentially a peripheral phenomenon. For wide masker separations, inhibition processes produce localized effects in the masking pattern.

APPENDICES

APPENDIX A

TWO INTERVAL FORCE CHOICE (2IFC) EQUIPMENT

The 2IFC method of signal presentation required the use of a locally manufactured random channel selector (RCS). The RCS performs the following functions on each trial: (1) randomization of the signal between the two temporal intervals; (2) turn on warning light; and (3) provide start trigger to interval timer controlling temporal interval one. Each temporal interval is controlled by its own electronic switch and timer.

Each trial begins with the "start" button press initiating the timing sequence in Fig. 12. The RCS input (test signal) is switched between the input of the two electronic switches at a rate of 10 kHz. A "start" button press operates the RCS until the end of the warning light period. At that instant the RCS delivers a signal to the input of either switch 1 (interval one) or switch 2 (interval two). The probability that the signal occurred in one interval or the other was found not to be statistically different from 0.5. A record of the interval selected was kept and checked periodically. One second following initiation of the trial, the RCS turned on a 500 msec warning light; 500 msec after the light went off, the "A" triggering pulse was delivered to interval timer

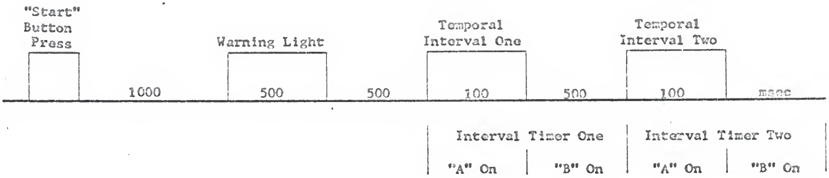

Fig. 12. Timing sequence for 2IFC.

one (Grason-Stadler, Model 471-1). The interval timer turned on electronic switch one for 100 msec with rise-fall time of 10 msec. A light was provided which coincided with temporal interval one. Following temporal interval one, a 500 msec interval ("B" on interval timer one) occurred separating temporal intervals one and two. Ending this interval was the "A" triggering pulse to interval timer two. Timer two turned on electronic switch two for 100 msec with rise-fall time of 10 msec. A second light coincided with temporal interval two. At the end of "B" on for interval timer two, the timers and switches were reset to their initial conditions. After the occurrence of both temporal intervals, the subject responded with the temporal interval thought to contain the signal. The response was manually recorded along with the stimulus level and interval the signal occurred in. The next trial began when the subject again pressed the "start" button.

APPENDIX B

SIGNAL AND MASKER GENERATION

The frequencies required to generate combined masker (C) with a 500 Hz spacing are 19,750 and 20,250 Hz. The frequency required for the test signal is 20,000 Hz. In amplitude modulation the carrier frequency determines the frequency location of the sidebands. With a carrier frequency of 20,400 Hz, the lower sideband frequencies are 150, 400 and 650 Hz. The upper sideband is eliminated by the frequency response of the earphone and filter. For the masker-above condition (A), 20,250 Hz is removed from the modulation input. For the masker-below condition (B), 19,750 Hz is removed from the modulation input. Variation of the carrier frequency from 20,400 to 23,000 Hz changes the signal from 400 to 3000 Hz with the masker component(s) located 250 Hz away.

APPENDIX C

DATA IN FIGS. 5 AND 6

Table 1. Mean SPL required for 75 per cent correct detections. Masker spacing in the combined condition was 100 Hz. The conditions are: masker-above (A), masker-below (B), and maskers-combined (C).

Test Frequency (Hz)	Subject 1			Subject 2		
	A	B	C	A	B	C
400	24.0	19.9	28.2	23.4	22.5	26.2
500	25.1	20.0	26.8	20.7	20.6	22.0
700	24.3	17.3	29.7	16.6	13.9	22.8
900	23.8	16.0	27.2	16.1	13.2	23.6
1000	24.4	20.0	30.1	18.7	14.7	23.1
1100	25.8	21.6	29.7	19.0	15.4	25.5
1200	23.6	21.5	30.5	19.9	17.9	26.1
1300	28.3	21.6	30.4	18.8	13.9	23.6
1400	28.6	23.6	29.6	18.5	16.6	22.8
1500	27.3	25.0	30.4	17.9	13.7	22.1
1600	27.7	23.6	33.0	14.4	14.6	24.5
1700	29.5	24.5	33.3	16.3	15.6	22.7
1800	27.2	25.3	28.6	17.8	17.0	24.8
1900	29.3	24.8	31.3	17.2	15.9	24.7
2000	28.7	24.0	30.5	16.5	15.9	24.4
2200	27.8	24.9	33.2	15.8	17.6	26.0
2400	29.4	23.8	30.7	15.2	16.3	24.8
2600	28.9	26.2	29.8	16.3	15.3	22.9
2800	28.2	23.9	29.4	15.3	14.3	22.6
3000	28.4	24.9	28.5	14.3	13.4	23.8

Table 2. Mean SPL required for 75 per cent correct detections. Masker spacing in the combined condition was 300 Hz. The conditions are: masker-above (A), masker-below (B), and maskers-combined (C).

Test Frequency (Hz)	Subject 1			Subject 2		
	A	B	C	A	B	C
400	15.0	16.9	17.0	20.2	22.1	21.4
500	15.0	13.2	20.1	19.4	18.8	20.8
700	12.0	9.8	15.6	16.0	14.3	17.7
900	14.3	8.8	16.5	14.7	7.5	16.8
1000	17.8	11.3	19.5	13.8	10.1	19.5
1100	20.2	11.2	18.3	16.0	14.3	21.1
1200	19.9	9.0	20.6	17.0	11.4	19.6
1300	24.8	13.9	23.4	15.0	9.1	19.2
1400	22.1	14.5	25.8	11.3	10.2	16.9
1500	22.3	14.8	22.8	10.5	10.8	16.5
1600	23.8	15.0	25.8	11.3	12.1	18.1
1700	22.2	17.0	26.0	12.3	12.2	18.7
1800	25.0	18.2	25.4	15.7	13.4	19.3
1900	25.5	19.4	27.6	17.2	12.2	19.7
2000	25.3	17.9	27.4	15.9	13.2	19.1
2200	29.4	17.7	28.9	16.8	15.0	22.5
2400	28.0	19.7	30.4	16.0	16.5	21.3
2600	27.1	20.9	31.2	16.0	16.2	21.9
2800	29.4	19.7	30.8	16.1	15.0	19.0
3000	30.7	22.5	26.4	20.5	17.2	23.5

Table 3. Mean SPL required for 75 per cent correct detections. Masker spacing in the combined condition was 500 Hz. The conditions are: masker-above (A), masker-below (B), and maskers-combined (C).

Test Frequency (Hz)	Subject 1			Subject 2		
	A	B	C	A	B	C
400	16.1	14.2	13.5	17.8	20.9	23.8
500	13.2	11.0	12.9	16.5	19.4	16.9
700	8.3	6.9	9.5	13.8	12.7	17.1
900	11.6	2.7	13.3	10.7	7.5	13.4
1000	16.2	7.2	13.5	12.7	7.6	14.1
1100	16.1	8.5	13.7	12.6	8.7	16.8
1200	15.1	7.7	14.7	12.3	8.1	13.1
1300	12.1	4.4	17.2	9.4	8.0	12.0
1400	17.0	8.1	18.6	6.6	7.3	10.1
1500	18.9	6.1	20.4	6.1	7.8	9.7
1600	15.0	6.5	15.6	10.2	9.3	12.4
1700	15.0	7.3	17.1	11.4	9.2	14.0
1800	20.9	9.5	17.0	12.1	11.7	14.9
1900	19.1	11.6	19.8	15.1	12.3	14.6
2000	19.2	9.0	22.0	12.1	9.8	14.8
2200	24.5	11.7	24.4	15.4	12.9	16.3
2400	25.4	14.4	24.7	17.3	15.3	18.1
2600	24.5	9.9	27.4	15.5	15.6	18.2
2800	27.7	15.8	29.4	18.1	15.6	18.6
3000	28.2	14.0	24.9	18.4	16.4	22.7

Table 4. Mean SPL required for 75 per cent correct detections in quiet.

Frequency	Subject 1	Subject 2
400	14.7	21.2
500	11.8	21.1
700	7.3	15.3
900	3.8	6.9
1000	7.5	6.5
1100	5.1	9.0
1200	4.9	7.5
1300	7.5	6.7
1400	8.6	8.2
1500	6.2	5.8
1600	6.4	8.2
1700	4.2	10.0
1800	9.7	12.9
1900	10.8	11.7
2000	7.9	9.1
2200	7.5	11.2
2400	13.1	17.7
2600	6.6	16.0
2800	8.8	14.7
3000	7.9	17.8

BIBLIOGRAPHY

von Békésy, G. (1960). Experiments in Hearing. McGraw-Hill Book Company, New York.

Bilger, R. (1959). "Additivity of Different Types of Masking," J. Acoust. Soc. Amer. 31, 1107-1109.

Bilger, R. C. and Hirsh, I. J. (1956). "Masking of Tones by Bands of Noise," J. Acoust. Soc. Amer. 28, 623-630.

Booth, J. C. and Brandt, J. F. (1970). "Masking by Double-Sideband Suppressed Carrier Amplitude-Modulated Sinusoids," J. Acoust. Soc. Amer. 48, 77(A).

Bos, C. E. and de Boer, E. (1966). "Masking and Discrimination," J. Acoust. Soc. Amer. 39, 708-715.

Brandt, J. F. and Booth, J. C. (1970). "Variations in Two-Tone Masking Paradigms," J. Acoust. Soc. Amer. 48, 77(A).

van den Brink, G. (1964). "Detection of Tone Pulse of Various Durations in Noise of Various Bandwidths," J. Acoust. Soc. Amer. 36, 1206-1211.

Campbell, R. A. (1969a). "Context and Sequence Effects with an Adaptive Threshold Procedure," J. Acoust. Soc. Amer. 46, 350-355.

Campbell, R. A. (1969b). "Thresholds re Duration and Levels of a Continuous or Gated Masker," J. Acoust. Soc. Amer. 46, 895-897.

Campbell, R. A., Hutton, C. L. and Stuckey, C. W. (1966). "Computerized Investigation of Threshold Decision Phenomenon," J. Acoust. Soc. Amer. 39, 1034-1036.

Campbell, R. A. and Lasky, E. Z. (1968). "Adaptive Threshold Procedures: BUDTIF," J. Acoust. Soc. Amer. 44, 537-541.

Carter, N. L. and Kryter, K. D. (1962). "Masking of Pure Tones and Speech," J. Auditory Res. 2, 66-98.

Carterette, C. C., Friedman, M. P. and Lovell, J. D. (1969). "Mach Bands in Hearing," J. Acoust. Soc. Amer. 45, 986-998.

Deatherage, B. H., Bilger, R. C. and Eldredge, D. H. (1957). "Remote Masking in Selected Frequency Regions," J. Acoust. Soc. Amer. 29, 512-514.

Egan, J. P. and Hake, H. W. (1950). "On the Masking Pattern of a Simple Auditory Stimulus," J. Acoust. Soc. Amer. 22, 622-630.

Ehmer, R. H. (1959). "Masking Patterns of Tones," J. Acoust. Soc. Amer. 31, 1115-1120.

Feldtkeller, R. and Zwicker, E. (1956). Das Ohr als Nachrichtenempfanger. S. Hirzel, Stuttgart.

Finck, A. (1961). "Low-Frequency Pure-Tone Masking," J. Acoust. Soc. Amer. 33, 1140-1141.

Fletcher, H. (1940). "Auditory Patterns," Rev. Mod. Phys. 12, 47-65.

Goldstein, J. L. (1967). "Auditory Nonlinearity," J. Acoust. Soc. Amer. 41, 676-689.

Green, D. M. (1965). "Masking with Two Tones," J. Acoust. Soc. Amer. 37, 802-813.

Green, D. M. (1967). "Additivity of Masking," J. Acoust. Soc. Amer. 41, 1517-1525.

Greenwood, D. D. (1961a). "Auditory Masking and the Critical Band," J. Acoust. Soc. Amer. 33, 484-502.

Greenwood, D. D. (1961b). "Critical Bandwidth and the Frequency Coordinates of the Basilar Membrane," J. Acoust. Soc. Amer. 33, 1344-1356.

Hamilton, P. M. (1957). "Noise Masked Thresholds as a Function of Tonal Duration and Masking Noise Bandwidth," J. Acoust. Soc. Amer. 29, 506-511.

Hawkins, J. E. and Stevens, S. S. (1950). "The Masking of Pure Tones and of Speech by White Noise," J. Acoust. Soc. Amer. 22, 6-13.

The Microelectronics Data Book. Motorola Semiconductor Products, Inc., 2nd Edition, December, 1969, Phoenix.

Plomp, R. (1965). "Detectability Threshold for Combination Tones," J. Acoust. Soc. Amer. 37, 1110-1123.

Rhode, W. S. (1971). "Observations of the Vibration of the Basilar Membrane in Squirrel Monkeys Using the Mössbauer Technique," J. Acoust. Soc. Amer. 49, 1218-1231.

Saito, S. and Watanabe, S. (1961). "Normalized Representation of Noise-Band Masking and Its Application to the Prediction of Speech Intelligibility," J. Acoust. Soc. Amer. 33, 1013-1021.

Schafer, T. H., Gales, R. S., Shewmaker, C. A. and Thompson, P. O. (1950). "Frequency Selectivity of the Ear as Determined by Masking Experiments," J. Acoust. Soc. Amer. 22, 490-497.

Scharf, B. (1970). Critical Bands. In J. V. Tobias (Ed.), Foundations of Modern Auditory Theory. Vol. 1, Academic Press, New York.

Shower, E. G. and Biddulph, R. (1931). "Differential Pitch Sensitivity of the Ear," J. Acoust. Soc. Amer. 3, 275-287.

Small, A. M. (1959). "Pure-Tone Masking," J. Acoust. Soc. Amer. 31, 1619-1625.

Spieth, W. (1957). "Downward Spread of Masking," J. Acoust. Soc. Amer. 29, 502-505.

Webster, J. C., Miller, P. H., Thompson, P. O. and Davenport, E. W. (1952). "The Masking and Pitch Shifts of Pure Tones Near Abrupt Changes in a Thermal Noise Spectrum," J. Acoust. Soc. Amer. 24, 147-152.

Wegel, R. L. and Lane, C. E. (1924). "The Auditory Masking of One Pure Tone by Another and Its Probable Relation to the Dynamics of the Inner Ear," Phys. Rev. 23, 266-284.

Zwicker, E. (1954). "Die Verdeckung von Schmalbandgeräuschen durch Sinustöne," Acustica 4, 415-420.

BIOGRAPHICAL SKETCH

John C. Booth, II, was born September 27, 1942, at Macon, Georgia. He was graduated from Hialeah High School in June, 1960. He attended Miami Dade Junior College and in January, 1961, entered the United States Air Force for four years. In January, 1965, he resumed his education at the University of Florida, receiving the degree of Bachelor of Arts in December, 1967. In January, 1968, he enrolled in the Graduate School of the University of Florida and held a traineeship from the Vocational Rehabilitation Administration. He received the degree of Master of Arts in June, 1969. Since then he has pursued studies leading toward a Doctor of Philosophy degree.

John Booth is married to the former Susan Baker and is the father of two children. He is a member of the Acoustical Society of America.

I certify that I have read this study and that in my opinion it conforms to acceptable standards of scholarly presentation and is fully adequate, in scope and quality, as a dissertation for the degree of Doctor of Philosophy.

John F. Brandt

John F. Brandt, Chairman
Associate Research Professor of Speech

I certify that I have read this study and that in my opinion it conforms to acceptable standards of scholarly presentation and is fully adequate, in scope and quality, as a dissertation for the degree of Doctor of Philosophy.

G. Paul Moore

G. Paul Moore
Professor of Speech

I certify that I have read this study and that in my opinion it conforms to acceptable standards of scholarly presentation and is fully adequate, in scope and quality, as a dissertation for the degree of Doctor of Philosophy.

Donald C. Teas

Donald C. Teas
Associate Professor of Speech

I certify that I have read this study and that in my opinion it conforms to acceptable standards of scholarly presentation and is fully adequate, in scope and quality, as a dissertation for the degree of Doctor of Philosophy.

Teruzo Konishi

Teruzo Konishi
Associate Research Professor of Surgery

I certify that I have read this study and that in my opinion it conforms to acceptable standards of scholarly presentation and is fully adequate, in scope and quality, as a dissertation for the degree of Doctor of Philosophy.

Arnold Paige

Arnold Paige
Associate Professor of Speech

I certify that I have read this study and that in my opinion it conforms to acceptable standards of scholarly presentation and is fully adequate, in scope and quality, as a dissertation for the degree of Doctor of Philosophy.

Madelaine M. Ramey

Madelaine M. Ramey
Assistant Professor of Psychology

This dissertation was submitted to the Department of Speech in the College of Arts and Sciences and to the Graduate Council, and was accepted as partial fulfillment of the requirements for the degree of Doctor of Philosophy.

August, 1971

Dean, Graduate School